NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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AN INVESTIGATION OF VERTICAL-WIND-SHEAR INTENSITIES FROM BALLOON SOUNDINGS FOR APPLICATION TO AIRPLANE- AND MISSILE-RESPONSE PROBLEMS

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SUMMARY

An analysis was made of the daily upper-wind soundings obtained from one station for a period of one year in an attempt to obtain measurements of the vertical wind shear in a form applicable to airplane- and missile-response problems. On the basis of the variation with altitude of the wind speed and direction indicated by the soundings, significant wind-shear layers were resolved into two crosscomponents, the so-called longitudinal and normal shears, and their intensities and thicknesses determined. These data are summarized in the form of frequency distributions of the shear intensity and the thickness of the shear layers for different altitude ranges and seasons of the year.

The results indicate maximum longitudinal shear intensities of about 100 meters per second per kilometer occurring at altitudes of 10 to 15 kilometers during the winter and spring months and maximum normal shear intensities of about 60 meters per second per kilometer. Only about 10 percent of the shear layers were greater than 1 kilometer in thickness. The application of these results on the wind-shear intensities to the calculation of the normal response of a missile in vertical flight at two different altitudés is also considered briefly.

INTRODUCTION

In the past, information on the wind velocities at different altitudes has been of interest in the operation of conventional military and commercial airplanes primarily because of the effect of the wind on the range or performance of the airplane. In particular, the wind speeds and directions at the optimum cruising altitudes are significant factors in flight planning. With the development of airplanes capable of high rates of climb or descent, the need has become urgent for more detailed information on the wind variations with altitude because of the effects of the large vertical wind gradients (wind shears) on the loads or motions of the airplane during high-speed climb or descent. This problem is also serious for missile operations since the accuracy of ballistic missiles and the requirements for the stability and control of guided missiles may be seriously affected by the response of the missile to intense vertical wind gradients during the vertical-flight portion of the trajectory. As a consequence, data are needed on the characteristics of the vertical wind shear at different altitudes.

A considerable amount of data on the wind speeds and directions at different altitudes is available from past investigations. The variations in the wind fields for altitudes up to about 30,000 feet (9 kilometers), for example, are discussed in some detail in reference 1. Examples of large wind shears in the vicinity of the jet stream near tropopause levels are given in references 2 and 3. For higher altitudes, reference 4 summarizes the average wind conditions as determined by various methods such as balloon soundings, sound-propagation studies, and the drift of smoke puffs from bursting smoke shells. In most of these cases, however, the data are not in a form suitable for determining the magnitude and frequency of occurrence of the vertical wind shears at given altitudes for use in design studies of the loads and motions of airplanes or missiles.

In order to provide the designer with information on the magnitude and frequency of occurrence of the vertical wind shears to altitudes of about 100,000 feet (30 kilometers), a study of wind data obtained from balloon soundings was undertaken by the National Advisory Committee for Aeronautics with the cooperation of the Office of Climatology, U.S. Weather Bureau. For this study, the daily upper-air soundings taken at the Weather Bureau station at Silver Hill, Maryland, for a period of one year were used to determine the shear layers from the variations in the wind velocity and the altitude intervals over which these variations occurred. The calculations for the shear layers utilized the facilities of the National Weather Records Center, Ashville, North Carolina. Although data on the wind velocities obtained from balloon soundings are recognized as being limited both in altitude and in the reliability of the observations by the performance of the surface tracking equipment, the soundings offered the only available source of statistical data on the wind shears.

In this report, the data on the vertical wind shears evaluated from the Silver Hill soundings for the one-year period are presented in a form suitable for assessing various airplane- and missile-response problems. The method of evaluating the soundings is described together with a consideration of the accuracies involved. As an indication of some applications of the data, an example is then given of the calculated normal response of a ballistic missile to a typical wind-shear layer.

SYMBOLS

h	altitude, km
Δh	altitude increment, km
S	vertical wind shear between reference altitude and next highest altitude level, mps/km
ΔS	increment of wind shear for successive altitude intervals above reference altitude, mps/km
S'	vertical wind shear for a given shear layer, mps/km
V	wind velocity, mps
ΔV	wind-velocity increment or wind gradient, mps
α	wind direction, deg
ϵ	elevation angle, deg
σ	root-mean-square (rms) error of designated quantity

Subscripts:

0	reference altitude or adjusted value
1,2,...n	successive altitudes above reference altitude

A bar over a symbol indicates the mean value.

DEFINITIONS

Vertical wind shear - The average wind gradient in the vertical; the difference in the wind velocities at an upper and a lower altitude divided by the altitude increment, $\frac{\Delta V}{\Delta h}$.

Longitudinal wind shear - A component of the vertical wind shear for the case in which the wind velocity at the upper altitude is the velocity component parallel to the wind direction at the lower altitude.

Normal wind shear - A component of the vertical wind shear for the case in which the wind velocity at the upper altitude is the velocity component normal to the wind direction at the lower altitude.

Shear layer - An altitude interval for which the calculated longitudinal or normal wind shear is equal to or greater than 6 mps/km.

SCOPE OF DATA AND APPARATUS

The data available for the present study consisted of the daily 0300 and 1500 G.m.t. (10:00 p.m. and 10:00 a.m. e.s.t.) wind soundings taken at the Weather Bureau observatory at Silver Hill, Maryland, from July 1, 1953, to July 1, 1954. These soundings were taken with the AN/GMD-1 rawin system. Briefly, this system consists of radio-direction-finding and radiosonde equipment. The direction finder automatically tracks a balloon-borne transmitter and records the elevation and azimuth angles at 0.1-minute time intervals. The radiosonde equipment provides simultaneous data on the air temperature, pressure, and humidity which are used to determine the altitude of the balloon. The track of the balloon as computed from the altitude and the elevation and azimuth angles then provides the information on the wind speed and direction at different altitudes. In the routine evaluation of the rawin data, average values of the wind speed and direction are determined at consecutive 1-minute time intervals from the time history of the flight path of the balloon. Since the rate of ascent of the balloons used in the present soundings was approximately 1,000 feet per minute, the wind observations were obtained at about 1,000-foot altitude intervals.

The altitude coverage of the Silver Hill data is indicated in figure 1 in terms of the number of soundings which reached various altitudes during the one-year observing period.

EVALUATION OF DATA

General Considerations

In developing the method of evaluating the soundings, both the characteristics of the wind data available and the properties of the disturbances important to the airplane response were considered. As an illustration of the characteristics of the wind data, several of the Silver Hill soundings are shown in figure 2. The soundings in figure 2 were selected to illustrate some of the extreme variations in wind speed and wind direction which were indicated by the data.

The outstanding features of figure 2(a) are the large variations in wind speed which are indicated by the soundings for altitudes between 9 and 19 kilometers. For the largest of these variations (the sounding of December 23, 1953), the wind speed increases sharply from about 40 mps at 13.6 kilometers to 117 mps at 14.5 kilometers and then decreases rapidly to 20 mps at 16.7 kilometers. Such large fluctuations in wind speed would result in intense wind shears over consecutive altitude intervals of 0.9 and 2.2 kilometers. Figure 2(a) also shows that only small changes in wind direction are associated with the large speed fluctuations. In figure 2(b), large variations in wind speed are also indicated near tropopause levels, but the significant features are the large and erratic variations in the wind direction indicated for the higher altitudes. For the sounding of December 12, 1953, in particular, almost a complete reversal of wind direction is shown between altitudes of 19.2 and 20.3 kilometers. Although the wind speeds are relatively low and constant over this altitude interval, such a large change in wind direction would result in a large wind shear over a depth of 1.1 kilometers.

In evaluating these soundings for data pertinent to the response of an airplane in vertical flight, the important quantities appeared to be the intensities of the wind shears and the thicknesses of the shear layers. In addition, since the important velocity components for studies of the loads or motions of an airplane in atmospheric disturbances are usually those acting normal to the wing or tail surfaces, it was considered desirable to resolve the wind shear into two crosscomponents. Although different sets of reference axes could be used to specify the two components, the maximum shear values resulting from the variations with altitude of both wind speed (fig. 2(a)) and wind direction (fig. 2(b)) could best be represented by using the wind direction at the base of the shear layer as a reference. In the subsequent evaluation of the Silver Hill soundings, the component in the direction of the wind at the base of the shear layer is referred to as the longitudinal shear. The component perpendicular to the longitudinal shear is referred to as the normal shear.

Method of Evaluation

Evaluation of soundings.- In order to illustrate the method of evaluating the two components of the wind shear, the results from a section of a sounding are given in figure 3. For the evaluation, the wind vector at the surface is taken as a reference and the wind vector at the next highest altitude is then resolved into components along and normal to the direction of the surface wind. The average wind shear for each component of this layer is then given by the difference between each component and the surface wind speed divided by the altitude interval between the two levels. For the longitudinal component of the first altitude interval in figure 3, the shear S is given by

$$S = \frac{V_1 \cos(\alpha_1 - \alpha_0) - V_0}{h_1 - h_0} \qquad (1)$$

In evaluating the data, it is of course necessary to set some lower limit or threshold which is based on both the accuracy of the data and the values which become unimportant to the airplane response. From such considerations of the data, a threshold of 6 mps/km was established for the evaluation.

If the value of S determined by equation (1) is less than the threshold of 6 mps/km, the wind shear is discarded. The wind vector V_1 in figure 3 is then taken as the new reference, and the calculation for the component of wind shear in the direction of V_1 and between altitudes h_1 and h_2 is similarly made. If the new value is also less than the threshold, it is discarded and V_2 is taken as the reference. If, however, the value of S as determined by equation (1) is 6 mps/km or greater, the extent of the shear layer is determined by calculating the longitudinal component of the wind shear for the next altitude interval. By referring to figure 3, this calculation for the shear increment ΔS can be made from the relation

$$\Delta S = \frac{V_2 \cos(\alpha_2 - \alpha_0) - V_1 \cos(\alpha_1 - \alpha_0)}{h_2 - h_1} \tag{2}$$

For the cases where ΔS is less than 6 mps/km, the original value of S is the desired wind shear, and the thickness of the shear layer is $h_1 - h_0$. For the cases where ΔS is equal to or greater than 6 mps/km, the calculation indicated by equation (2) is repeated for vectors V_3, V_4, . . . V_n until a value less than the threshold is obtained. This point then indicates the top of the shear layer. The final value for the longitudinal component of the shear for the layer is given by

$$S' = \frac{V_n \cos(\alpha_n - \alpha_0) - V_0}{h_n - h_0} \tag{3}$$

In proceeding with the calculations, the upper altitude h_n now becomes the reference for the next shear layer. In these calculations a wind-shear layer includes only those values of ΔS which are in the same direction as the shear for the initial interval; that is, ΔS must have the same sign as S. Also, the shear values represent only the average velocity gradient over a given altitude interval. The method of computing the winds from the recorded surface data, in addition, tends to smooth the sharper velocity fluctuations which may occur between the approximate 1,000-foot observing intervals.

The steps for calculating the normal component of wind shear are similar to those given for the longitudinal component except that the cosine function is replaced by the sine function and, of course, V_0 drops out of equations (1) and (3). The value for the normal component of the shear for a given layer is given by

$$S' = \frac{V_n \sin(\alpha_n - \alpha_0)}{h_n - h_0} \tag{4}$$

For further information on the method of evaluation, the calculations for the longitudinal shear components and the altitudes and thicknesses of the shear layers for the sounding of December 23, 1953 (fig. 2(a)) are summarized in table I. In figure 4, the absolute values of both the longitudinal and the normal components of the wind shear evaluated from 20 soundings for the 10- to 15-kilometer altitude interval are plotted against the thickness of the shear layers to illustrate the general characteristics of the data obtained.

Evaluation for effect of measurement errors.- As has been indicated previously, the wind measurements from the rawin system are subject to error because of limitations in the performance of the surface radio-direction-finding and radiosonde equipment. These errors in the wind observations become particularly serious at high altitudes for strong winds and low elevation angles and, of course, propagate large errors in the shears calculated from the wind speeds, directions, and altitudes. It thus becomes important to evaluate the magnitude of these errors in the wind shears. The method used for evaluating the effect of these measurement errors on the wind-shear data is given in the appendix. Briefly, the method consists of estimating the root-mean-square error in the wind speeds and directions from the inherent observational errors of the rawin system. The wind-measurement errors depend upon such factors as the elevation angle and altitude of the balloon; consequently, it was necessary to examine the wind speeds and directions pertinent to each shear measurement. The resulting root-mean-square error in each shear layer was then determined.

These calculations for the effect of the instrument errors on the shear intensities indicated that many of the shear values were meaningless since the root-mean-square error for these cases was equal to or even greater than the value of the wind shear. As examples of the relative magnitude of the errors associated with the wind-shear values, the root-mean-square errors are given in figure 4 for several of the longitudinal and normal shear layers. For higher altitudes and strong winds the relative magnitude of the errors may become appreciably greater than for the cases shown in figure 4 because of the low elevation angles. (See appendix.)

In an attempt to sort out the unreliable data, all shear layers in which the root-mean-square error was greater than the computed shear were discarded. As an additional check on the data, a detailed examination was made of the soundings which indicated extremely erratic winds, particularly erratic changes in wind direction at high altitudes for high wind speeds. Such cases in which large fluctuations in wind direction occurred between the consecutive 1,000-foot recording intervals were considered as reading or recording errors and were not included in the results. In addition, all values for which the elevation angle was less than 7° were considered questionable and were discarded because of the large errors associated with these readings. This screening of the data resulted in discarding approximately 10 percent of the shear layers calculated for altitudes less than 15 kilometers and 30 percent of the shear layers calculated for altitudes greater than 15 kilometers. The shear data are thus probably biased to the extent that the intense shears at high altitudes and strong winds are not suitably represented.

RESULTS

The soundings were evaluated for the longitudinal and normal components of the wind shear and the depth of the shear layers by means of the procedures discussed in the preceding section. As would be expected, considerable variation existed in the intensities and altitudes of the shear layers from one sounding to another. In order to determine the overall altitude and seasonal variations in the wind shears, the data were grouped by 5-kilometer altitude intervals for the four seasons: spring, March through May; summer, June through August; fall, September through November; and winter, December through February.

An inspection of these results indicated that the positive and negative values of the shear intensities were about equal in number and were symmetrically distributed about the threshold value. The positive and negative values were accordingly combined and the resulting frequency distributions are given in table II for shear intervals of 5 mps/km and for the 5-kilometer altitude intervals of each season of the year. The total number of shear layers, the number of soundings obtained at each altitude interval, and the average number of shear layers for each sounding are also given in table II to indicate the sample size and the average frequency of occurrence of the shear layers. In addition, the root-mean-square shear $\left(\overline{S'^2}\right)^{1/2}$ obtained from each of the distributions is given to provide a measure of the shear intensity for the different altitudes and seasons. An increased root-mean-square value, in general, indicates a greater probability of exceeding the larger shear intensities. These values are not given for the 25- to 30-kilometer altitude interval of the spring and winter seasons because the data represent only three soundings.

Although table II summarizes only the more reliable data on the shears, random errors are still associated with each value in the table. No simple method appeared available to account for these errors. As a measure of the relative reliability of the data for the various altitudes and seasons, however, the root-mean-square value of the errors $\left(\overline{\sigma_{S'}^2}\right)^{1/2}$ is also given for each distribution. The appreciably larger errors associated with the data at the highest altitudes are apparent from a comparison of the values of $\left(\overline{\sigma_{S'}^2}\right)^{1/2}$ in the table.

Since the data in table II represent only the intensity of the average shear gradients and provide no information on the thickness or the vertical extent of the shear layers, the data were also sorted to examine the layer thicknesses for variation with altitude, shear intensity, and season of the year. Sample distributions indicating the probability that given layer thicknesses would be exceeded are shown in figure 5 for both the longitudinal and normal shear components and for the different altitude intervals of the winter season. In figure 6, the probability distributions are shown for different ranges of longitudinal shear intensity for the winter season. Other distributions also indicated only minor variation in layer thickness for the different altitudes, seasons, or shear intensities and are not shown.

DISCUSSION OF WIND-SHEAR MEASUREMENTS

The results presented indicate the general characteristics of the shear layers as obtained from an analysis of balloon soundings. As has been indicated, these results provide measurements of only the average shear gradients for layer thicknesses greater than about 0.3 kilometer and are limited in accuracy, particularly at the higher altitudes. The data, however, provide information on at least the general level of the shear intensities and their frequencies of occurrence and afford a basis for assessing the significance of the shears in regard to airplane or missile behavior. Some details of the results obtained are discussed in the following paragraphs.

Shear Intensities and Frequencies

Very intense longitudinal shears of 100 mps/km or greater are indicated in table II for the winter and spring months and of about 80 mps/km for the summer and fall months. As has been noted, the normal shear intensities are of smaller magnitude but the maximum intensities are still about 50 to 60 mps/km. These results indicate that intense vertical wind shears may be encountered by an airplane or missile in vertical flight, particularly at altitudes from 10 to 25 kilometers.

An indication of the average number of shear layers which might be expected for such flights may be obtained by considering the average number of shear layers per sounding in table II. For the more intense shears, table II(a) indicates 25 cases with intensities greater than 50 mps/km for the spring season at altitudes from 10 to 15 kilometers. Based on the 171 soundings for this altitude interval, a shear layer with an intensity greater than 50 mps/km would be expected on the average once in seven soundings (or flights). Although these values give no indication of the number of intense shear layers that might occur for a given flight, an examination of individual wind profiles (such as in fig. 2) indicated that "fingers" or adjacent layers of high wind were common to many soundings. It thus appears that several intense shear layers would be encountered in some cases.

Altitude or seasonal variations in the wind-shear data in table II may be estimated by comparing the values of the root-mean-square shear intensities $\left(\overline{S'^2}\right)^{1/2}$ at the different altitudes and the associated root-mean-square errors $\left(\overline{\sigma_{S'}{}^2}\right)^{1/2}$. For these root-mean-square values, increased root-mean-square errors would result in increased root-mean-square shear intensities. On this basis, a comparison of the values in the table indicates that the root-mean-square shear intensities $\left(\overline{S'^2}\right)^{1/2}$ are reasonably representative at the lower altitudes but are much too large at the higher altitudes. As a consequence, the data in table II suggest a general maximum in the shear intensities at about tropopause levels for the winter and spring seasons.

Layer Thickness

Figures 5 and 6 indicate no appreciable effects of altitude or shear intensity, respectively, on the layer thicknesses. The figures also indicate that only about 10 percent of the shear layers encountered by an airplane or missile would be greater than 1 kilometer in thickness. It might be again noted in this connection that the minimum measurable layer thickness was about 0.3 kilometer. The tendency for somewhat thicker layers of normal shear to occur at altitudes from 0 to 10 kilometers than at higher altitudes (fig. 5(b)) probably results from the variable winds usually found at low altitudes.

Since the combination of both the layer thickness and the shear intensity is of interest in considering airplane or missile response, the following examples are given for several of the more severe longitudinal shear layers measured from the soundings. Shear intensities of 106, 110, and 125 mps/km were associated with layer thicknesses of 1.3, 0.67, and 0.62 kilometers, respectively. Other typical values were shear intensities of 61, 80, and 90 mps/km which had thicknesses of 1.5, 0.36, and 0.76 kilometers, respectively. As has been indicated, the layers of normal shear covered about the same range of thicknesses but the intensities were less.

Geographical Representativeness

As has been mentioned previously, data on the wind shear are available from other investigations. Comparison of these data indicated large variations, as would be expected for the different geographical locations. The results are summarized briefly in the following paragraph to indicate the differences in the shear intensities which might be attributed to geographical effects.

An examination of the wind soundings given in reference 5 indicates maximum vertical wind shears of about 135 mps/km at an altitude of 23 kilometers over Japan during the winter season. The layers were less than 1 kilometer in thickness for these extreme cases. For layers greater than 1 kilometer in thickness, the data indicate maximum shears of about 80 mps/km. An evaluation of a small number of wind soundings taken over England (ref. 6) during one month from each season of the year indicates maximum vertical wind shears of about 25 mps/km at altitudes from 20,000 to 40,000 feet. Reference 1 cites vertical wind shears of about 100 mps/km which were observed at an altitude of 30,000 feet during airplane research flights over Australia. The thicknesses of the layers over which these shears were measured are not given. Reference 7 illustrates several cases in which vertical wind shears up to 60 mps/km were observed during jet-stream occurrences over eastern and midcontinental locations in the United States. The thicknesses of the shear layers cannot be determined accurately from the vertical-wind profiles given in the reference, although the layers appear to be less than 1 kilometer thick.

The results of these different investigations suggest sizable variations in the shear intensities for the different locations. For locations under the influence of severe jet-stream activity - such as evidenced by the data from Japan in reference 5 - more severe shear intensities than given in table II may be expected.

EFFECT OF WIND SHEAR ON MISSILE RESPONSE

As an indication of the effect of a given wind-shear layer on the loads and motions of an airplane or missile in vertical flight, calculations were made for the acceleration and translation, normal to the longitudinal axis, of a ballistic missile traversing a wind-shear layer at altitudes of 35,000 and 70,000 feet. For these calculations, a single shear gradient of 100 mps/km extending over a depth of 1 kilometer was selected as being representative of the more intense shears of table II. A missile configuration with high mass and low damping of the short period was selected as being typical of current ballistic missiles. The values for the missile parameters used in the calculations were based on available wind-tunnel-test data at a representative flight Mach number for the type of missile under consideration.

In performing the calculations, the normal response of the missile to a linear-gradient shear layer was obtained by superposition from the calculated missile response to a unit step gust. The acceleration response at the center of gravity for a unit step was determined by means of a solution to the equations of motion given in reference 8 for the case of a rigid missile free to move in a direction normal to its longitudinal axis and to pitch about its center of gravity.

The results of the calculations indicated a maximum acceleration increment of about 0.6g and a lateral displacement of about 6 feet at an altitude of 35,000 feet. At an altitude of 70,000 feet, the corresponding values were about 0.3g and 3 feet, respectively. Check calculations for several other tailed and tailless missile configurations and current fighter airplanes traversing the shear layer indicated maximum acceleration increments up to about 1.5g. Although these values of acceleration may be significant, they still appear somewhat small compared with the accelerations expected for high-speed airplane or missile flights through more severe turbulence such as may be encountered in thunderstorms.

CONCLUDING REMARKS

The analysis of the daily upper-wind soundings obtained from one station for a period of one year is an attempt to obtain vertical-wind-shear measurements in a form suitable for studying airplane- and missile-response problems. The results obtained on the shear intensities, frequencies of occurrence, and thicknesses of the shear layers and their variation with season and altitude are limited, both in regard to the accuracy of the results and the altitude range covered, by the performance of the surface tracking equipment. These results, however, provide a basis for assessing the significance of the shear layers on airplane or missile behavior.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
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APPENDIX

EFFECT OF MEASUREMENT ERRORS ON WIND-SHEAR CALCULATIONS

In estimating the errors in the wind-shear calculations, use is made of the errors in the measurements of wind speed, direction, and altitude which are inherent in the rawin observations. Estimates of these errors in the wind measurements are based on the results obtained from a Signal Corps study of the performance of the AN/GMD-1 rawin set (ref. 9) and results obtained at the Langley Aeronautical Laboratory.

The Signal Corps study indicates that the standard (root-mean-square) errors in the various quantities measured with the rawin system are as follows:

Absolute elevation and azimuth angles, deg	0.1
Incremental elevation and azimuth angles, deg	0.05
Absolute pressure, altitude less than 40,000 feet, mb	3
Absolute pressure, altitude greater than 40,000 feet, mb	1.5
Incremental pressure, mb	1

These instrument errors are used in reference 9 to derive the resulting errors in the wind velocity. A comparison of the results given in reference 9 for the different instrument errors indicates that significant contributions to the errors in the wind velocity arise from the errors in the incremental elevation angle and the incremental and absolute pressures. On the basis that these instrument errors are random and independent, the resulting root-mean-square error in the wind velocity may be obtained from the square root of the sum of the squares of the individual errors in the measurements. This root-mean-square error in the wind velocity is shown in figure 7 as a function of altitude and elevation angle. It will be noted from figure 7 that the root-mean-square error in wind velocity increases rapidly with increasing altitude and decreasing elevation angle.

The errors in the measurement of wind direction were estimated from a limited series of soundings taken at the Langley Aeronautical Laboratory in which both a modified SCR-584 radar-phototheodolite system and an AN/GMD-1 rawin system were utilized for balloon tracking. The soundings were made to altitudes of about 60,000 feet and represented wind velocities up to 50 or 60 miles per hour. The radar system is described in reference 10 and is considered as the most reliable method available at the present time for obtaining balloon positioning data. The differences between the wind directions computed for the radar and AN/GMD-1 rawin systems for simultaneous 1-minute observing intervals were used to determine the root-mean-square direction error of the AN/GMD-1 rawin system.

The resulting value was about 4° for the altitudes and wind conditions represented. This value of 4° was used to represent the root-mean-square wind-direction errors in the Silver Hill soundings.

Check calculations for a number of shear layers evaluated from the present data indicated that the effects of the errors in the altitude interval were small compared with the effects of the errors in the wind speed and direction (less than 10 percent). The errors in the thicknesses of the shear layers were accordingly neglected.

Conventional methods were used to estimate the root-mean-square errors in the longitudinal and normal components of the wind shears from the preceding values of the root-mean-square errors in wind velocity and direction. For the case of the longitudinal shear, the following expression given in the section entitled "Method of Evaluation" was used to evaluate the shear intensity:

$$S' = \frac{V_n \cos(\alpha_n - \alpha_0) - V_0}{h_n - h_0} \tag{5}$$

The errors in the wind shear S' resulting from the random errors in the measurements of V_n, V_0, α_n, and α_0 may then be expressed by the derivative of S'

$$dS' = \frac{1}{h_n - h_0}\left[-V_n \sin(\alpha_n - \alpha_0)(d\alpha_n - d\alpha_0) + \cos(\alpha_n - \alpha_0)dV_n - dV_0\right] \tag{6}$$

where the $d\alpha$ and dV terms are the errors in the wind directions and velocities, respectively, for the upper and lower altitudes of a given shear layer. Check calculations for a number of the longitudinal-shear layers indicated that the changes in wind direction were generally less than 5° for the significant shears and that neglecting these directional changes would result in discrepancies of less than 10 percent. The term containing the sine of the angle was accordingly dropped from the preceding equation, and the cosine of the angle was considered to be unity. On the basis that the errors represented by $d\alpha$ and dV are random and independent, the root-mean-square error in the computed values of the longitudinal shear components may then be obtained from the square root of the sum of the squares of the remaining terms, or

$$\sigma_{S'} = \frac{1}{h_n - h_0}\left({\sigma_{V_n}}^2 + {\sigma_{V_0}}^2\right)^{1/2} \tag{7}$$

where σ in each case indicates the root-mean-square error in the designated quantity.

For most values of the wind shear evaluated from the present soundings, the thickness of the shear layer $h_n - h_0$ was less than 2 or 3 kilometers and elevation-angle changes of less than 0.1° or 0.2° occurred between the rawin readings for the upper and lower altitudes. Inspection of figure 7 indicates that under these conditions only small differences would be determined for the root-mean-square errors in the wind velocity for the upper and lower altitudes of a shear layer, and, in order to simplify the calculations, σ_{V_n} was taken equal to σ_{V_0}. The relation for the root-mean-square error in the longitudinal component of the wind shear then becomes

$$\sigma_{S'} = \frac{1.4}{h_n - h_0}\sigma_V \tag{8}$$

A similar procedure was followed to estimate the root-mean-square errors in the normal components of the wind shear. The final expression for the root-mean-square error of the normal component of the shear is

$$\sigma_{S'} = \frac{1}{h_n - h_0}\left[2\sigma_\alpha^2 V_n^2 \cos^2(\alpha_n - \alpha_0) + \sigma_{V_n}^2 \sin^2(\alpha_n - \alpha_0)\right]^{1/2} \tag{9}$$

Many of the significant normal-shear layers resulted from large changes in wind direction; that is, $\alpha_n - \alpha_0$ was up to 45° or greater. Accordingly, both the sine and the cosine terms must be considered in calculating the value of $\sigma_{S'}$ for the normal-shear cases.

Substitution of the pertinent values of σ_V from figure 7 and the value of 4° (0.07 radian) for σ_α, together with the given values of h and α for each shear layer in equations (8) and (9), yields the root-mean-square errors in the longitudinal and normal components of the wind-shear layers.

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TABLE I.- CALCULATIONS FOR LONGITUDINAL SHEAR

Rawin data					Calculations for first altitude interval						
Time, min	Elevation angle, ϵ, deg	Altitude, h, km	Wind velocity, V, mps	Wind direction, α, deg	$\alpha_n - \alpha_{n-1}$, deg	$\cos(\alpha_n - \alpha_{n-1})$	$V_n \cos(\alpha_n - \alpha_{n-1})$, mps	$V_n \cos(\alpha_n - \alpha_{n-1}) - V_{n-1}$, mps	$h_n - h_{n-1}$, km	S, mps/km
0	——	0.088	4	330						
1	27.6	.330	12	332	2	0.99939	11.99	7.99	0.242	33.0
2	24.6	.690	13	321	-11	.98163	12.76	.76	.360	2.1
3	24.2	1.010	12	297	-24	.91355	10.96	-2.04	.320	-6.4
4	25.2	1.340	12	269						
5	27.2	1.700	16	252	-17	0.95630	15.30	3.30	0.360	9.2
6	26.1	2.050	23	247						
7	24.2	2.450	27	241						
8	22.4	2.830	29	234	-7	.99255	28.78	1.78	.380	4.7
9	20.9	3.200	32	233	-1	.99985	32.00	3.00	.370	8.1
10	19.4	3.570	32	233	0	1.00000	32.00	0	0.370	0
11	18.2	3.920	33	231	-2	.99939	32.98	.98	.350	2.8
12	17.0	4.280	37	234	3	.99863	36.95	3.95	.360	11.0
13	16.0	4.640	38	234	0	1.00000	38.00	1.00	.360	2.8
14	15.1	5.010	37	234	0	1.00000	37.00	-1.00	.370	-2.7
15	14.6	5.390	37	242	8	0.99027	36.64	-0.36	0.380	-0.9
16	14.0	5.760	44	252	10	.98481	43.33	6.33	.370	17.1
17	13.2	6.100	56	253						
18	12.1	6.430	61	252						
19	11.4	6.740	58	251	-1	.99985	57.99	-3.01	.310	-9.7
20	10.9	7.120	61	250	-1	0.99985	61.00	3.00	0.380	7.9
21	10.4	7.510	75	249						
22	9.8	7.950	80	246						
23	9.4	8.310	81	242	-4	.99756	80.80	.80	.380	2.1
24	8.8	8.660	78	241	-1	.99985	77.99	-3.01	.350	-8.6
25	8.6	9.040	81	240	-1	.99985	80.99	2.99	.380	7.9

COMPONENTS FOR SOUNDING OF DECEMBER 23, 1953

Calculations for extent of shear layer						Final shear calculations						
$\alpha_n - \alpha_0$, deg	$\cos(\alpha_n - \alpha_0)$	$V_n \cos(\alpha_n - \alpha_0)$, mps	ΔV, mps	$h_n - h_0$, km	ΔS, mps/km	$\alpha_n - \alpha_0$, deg	$\cos(\alpha_n - \alpha_0)$	$V_n \cos(\alpha_n - \alpha_0)$, mps	$V_n \cos(\alpha_n - \alpha_0) - V_0$, mps	$h_n - h_0$, km	S', mps/km	h_0, km
						2	0.99939	11.99	7.99	0.242	33.0	0.1
-9	0.98769	12.84	0.85	0.360	2.4							
-52	.61566	7.39	-3.57	.330	-10.8	-52	.61566	7.39	-3.61	.650	-8.6	.7
-69	0.35837	5.73	-1.66	0.360	-4.6							
-22	.92718	21.33	6.03	.350	17.2							
-28	.88295	23.84	2.51	.400	6.3	-28	0.88295	23.84	11.84	1.110	10.7	1.3
-35	.81915	25.76	.08	.380	.2							
						-1	.99985	32.00	3.00	.370	8.1	2.8
-1	0.99985	32.00	0	0.370	0							
						3	0.99863	36.95	3.95	0.360	11.0	3.9
3	.99863	37.95	1.00	.360	2.8							
11	0.98163	54.97	11.64	0.340	34.2							
10	.98481	60.07	5.10	.330	15.5	10	0.98481	60.07	23.07	1.040	22.2	5.4
9	.98769	57.29	-2.78	.310	-9.0	-1	.99985	57.99	-3.01	.310	-9.7	6.4
-2	0.99939	60.96	2.96	0.380	7.8							
-2	.99939	74.95	13.95	.390	35.8							
-5	.99619	79.70	4.75	.420	11.3	-5	0.99619	79.70	21.70	1.190	18.2	6.7
-4	.99756	80.80	1.10	.380	2.9							
						-1	.99985	77.99	-3.01	.330	-8.6	8.3
-2	.99939	80.95	2.95	.380	7.8							

TABLE I.- CALCULATIONS FOR LONGITUDINAL SHEAR COMPONENTS

Rawin data					Calculations for first altitude interval					
Time, min	Elevation angle, ϵ, deg	Altitude, h, km	Wind velocity, V, mps	Wind direction, α, deg	$\alpha_n - \alpha_{n-1}$, deg	$\cos(\alpha_n - \alpha_{n-1})$	$V_n \cos(\alpha_n - \alpha_{n-1})$, mps	$V_n \cos(\alpha_n - \alpha_{n-1}) - V_{n-1}$, mps	$h_n - h_{n-1}$, km	S, mps/km
26	8.3	9.480	99	240						
27	7.9	9.890	91	238	-2	0.99939	90.94	-8.06	0.410	-19.6
28	7.7	10.300	62	233						
29	7.7	10.640	80	237	4	.99756	79.80	17.80	.340	52.4
30	7.3	10.990	93	243						
31	7.2	11.440	90	243	0	1.00000	90.00	-3.00	0.450	-6.7
32	7.0	11.870	95	244	1	.99985	94.99	4.99	.430	11.6
33	6.9	12.220	103	248						
34	6.6	12.570	103	249	1	.99985	102.98	-.02	.350	-.1
35	6.4	12.900	100	251	2	.99939	99.94	-3.06	.330	-9.3
36	6.3	13.280	60	259						
37	6.3	13.620	40	256						
38	6.3	13.910	44	257	1	0.99985	43.99	3.99	2.90	13.8
39	6.3	14.210	60	261						
40	6.3	14.520	117	251						
41	6.1	14.940	100	246	-5	0.99619	99.62	-17.38	0.420	-41.4
42	6.1	15.330	48	240						
43	6.1	15.700	42	240						
44	6.1	16.030	40	240	0	1.00000	40.00	-2.0	.330	-6.1
45	6.2	16.370	35	246						
46	6.3	16.700	20	257						
47	6.3	17.000	46	250	-7	0.99255	45.66	25.66	0.300	85.5
48	6.3	17.310	67	246						
49	6.2	17.610	67	246	0	1.00000	67.00	0	.300	0
50	6.2	17.910	77	246	0	1.00000	77.00	10.00	.300	33.3
51	6.1	18.210	74	246	0	1.00000	74.00	0.300	0.300	-10.0
52	6.1	18.520	40	246						
53	6.1	18.830	22	246						

FOR SOUNDING OF DECEMBER 23, 1953 - Concluded

Calculations for extent of shear layer						Final shear calculations						
$\alpha_n - \alpha_0$, deg	$\cos(\alpha_n - \alpha_0)$	$V_n \cos(\alpha_n - \alpha_0)$, mps	ΔV, mps	$h_n - h_0$, km	ΔS, mps/km	$\alpha_n - \alpha_0$, deg	$\cos(\alpha_n - \alpha_0)$	$V_n \cos(\alpha_n - \alpha_0)$, mps	$V_n \cos(\alpha_n - \alpha_0) - V_0$, mps	$h_n - h_0$, km	S', mps/km	h_0, km
-1	0.99985	98.99	18.00	0.440	40.9	-1	0.99985	98.99	20.99	0.820	25.6	8.7
-3	.99863	90.88	-8.11	.410	-19.8							
-7	.99255	61.54	-18.52	.410	-45.2	-7	.99255	61.54	-3.75	.820	-45.7	9.5
-3	.99863	79.89	18.35	.340	54.0							
10	.98481	91.59	11.79	.350	33.7	10	.98481	91.59	29.59	.690	42.9	10.3
10	0.98481	88.63	-2.96	0.450	-6.6	0	1.00000	90.00	-3.00	0.450	-6.7	11.0
1	.99985	94.99	4.99	.430	11.6							
5	.99619	102.61	7.61	.350	21.7	5	.99619	102.61	12.61	.780	16.2	11.4
6	.99452	102.44	-.17	.350	-.5							
10	0.98481	59.09	-40.85	0.380	-107.5							
7	.99255	39.70	-19.39	.340	-57.0	7	0.99255	39.70	-63.30	1.050	-60.3	12.6
8	.99027	43.57	3.87	.290	13.3							
5	.99619	59.77	15.78	.300	52.6							
-5	.99619	116.55	56.78	.310	183.2	-5	.99619	116.55	76.55	.900	85.1	13.6
-10	0.98481	98.48	-18.07	0.420	-43.0							
-11	.98163	47.12	-52.50	.390	-134.6							
-11	.98163	41.25	-5.89	.370	-15.9	-11	0.98163	41.25	-75.77	1.180	-64.2	14.5
-11	.98163	39.27	-1.96	.330	-5.9							
16	.99452	34.81	-5.19	.340	-15.3							
17	0.95630	19.13	-15.68	0.330	-47.5	17	0.95630	19.13	-22.87	1.000	-22.9	15.7
10	.98481	45.30	26.17	.300	87.2							
-11	.98163	65.77	20.11	.310	64.9	-11	.98163	65.77	45.77	.610	75.0	16.7
-11	.98163	65.77	0	.300	0							
						0	1.00000	77.00	10.00	.300	33.3	17.6
0	1.00000	74.00	-3.00	0.300	-10.0							
0	1.00000	40.00	-34.00	.310	-109.7							
0	1.00000	22.00	-18.00	.310	-58.1	0	1.00000	22.00	-55.00	0.920	-59.8	17.9

TABLE II

FREQUENCY DISTRIBUTIONS OF WIND SHEAR

(a) Longitudinal component

Shear, mps/km	Frequency at altitude interval, km, of –											
	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30
	Spring						Summer					
6 to 11	473	406	224	132	46	2	443	428	369	253	130	23
11 to 16	147	181	177	129	43	1	71	122	175	135	26	9
16 to 21	48	67	100	66	22		21	31	81	58	19	1
21 to 26	29	35	67	54	19		28	11	30	24	3	
26 to 31	12	22	41	17	17		9	2	24	10	1	
31 to 36	4	7	21	11	9	2	6	2	10	10		1
36 to 41	8	7	26	8	1		1	4	3	5	1	
41 to 46	4	5	11	9	2				6	3		
46 to 51		4	14	6	4					2	1	
51 to 56	1	1	8	8	1					1		
56 to 61	1	2	3	4	2							
61 to 66	2	1	3	4								
66 to 71			2	1	1					1		
71 to 76		1	2	3						1		
76 to 81		1	1	1	1							
81 to 86		1	4	1								
86 to 91				2								
91 to 96			1									
96 to 101			1									
Total	729	741	706	436	168	5	579	600	698	503	181	34
Total soundings	182	181	171	146	103	3	181	178	176	161	130	39
Average number of shear layers per sounding	4.0	4.1	4.1	3.0	1.6	1.7	3.2	3.4	4.0	3.1	1.4	0.9
Root-mean-square shear, $\left(\overline{s'^2}\right)^{1/2}$	12.7	15.1	22.9	22.2	20.9	-	11.0	10.4	14.3	12.3	12.0	11.7
Root-mean-square error, $\left(\overline{\sigma_{s'}^2}\right)^{1/2}$	1.2	4.7	7.9	11.0	13.6	-	0.4	3.0	3.1	6.6	8.2	8.2

TABLE II.- Continued

FREQUENCY DISTRIBUTIONS OF WIND SHEAR

(a) Concluded

Shear, mps/km	Altitude interval, km											
	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30
	Fall						Winter					
6 to 11	415	369	283	220	96	21	455	324	155	60	24	
11 to 16	105	133	201	144	46	4	181	202	151	117	35	
16 to 21	25	42	92	58	25	4	61	88	130	92	26	2
21 to 26	16	9	38	30	15	2	36	60	95	59	16	1
26 to 31	17	4	17	16	13	2	15	25	52	41	10	
31 to 36	10	2	14	15	7	1	12	21	32	21	14	2
36 to 41	3	3	4	4	2		9	14	21	11	10	1
41 to 46	2		3	3			5	6	18	15	5	
46 to 51			5	1		1	1	4	13	11	2	
51 to 56					1		2	4	7	11	4	
56 to 61			1	1			1		11	6	1	
61 to 66								1	8	2	2	
66 to 71								1	4	4		
71 to 76									3	1		
76 to 81								1		1	1	
81 to 86			1	1				1	1			
86 to 91										2		
91 to 96										1		
96 to 101									1			
101 to 106											1	
106 to 111										1	1	
111 to 116												
116 to 121												
121 to 126									1	1		
Total	593	562	659	493	203	35	778	750	703	457	152	6
Total soundings	181	181	173	156	113	23	177	173	159	135	74	3
Average number of shear layers per sounding	3.3	3.1	3.8	3.2	1.8	1.5	4.4	4.3	4.4	3.4	2.0	2.0
Root-mean-square shear, $\left(\overline{s'^2}\right)^{1/2}$	11.5	10.7	15.7	14.1	11.7	16.2	12.3	13.9	25.6	25.7	25.6	-
Root-mean-square error, $\left(\overline{\sigma_{s'}^2}\right)^{1/2}$	0.6	3.2	5.7	7.6	10.8	11.8	1.2	5.3	9.4	12.7	16.3	-

TABLE II.- Concluded

FREQUENCY DISTRIBUTIONS OF WIND SHEAR

(b) Normal component

Shear, mps/km	Altitude interval, km											
	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30
	Spring						Summer					
6 to 11	379	188	228	323	162	10	325	247	320	421	288	65
11 to 16	96	56	129	112	59	2	53	33	95	139	60	16
16 to 21	32	12	50	40	22		16	1	23	42	14	2
21 to 26	15	3	16	17	8	1	1		6	21	5	
26 to 31	5		5	7	3		1		1	5	4	
31 to 36	1		3	4	1	1	1		1	2		
36 to 41		1		3						1		
41 to 46			1	1	3							
46 to 51	1			1			1			1		
51 to 56		1	1	1						1		
Total	529	261	433	509	258	14	398	281	446	633	371	83
Total soundings	182	181	171	146	103	3	181	178	176	161	130	39
Average number of shear layers per sounding	2.9	1.4	2.5	3.5	2.5	4.7	2.2	1.6	2.5	3.9	2.8	2.1
Root-mean-square shear, $\left(\overline{s'^2}\right)^{1/2}$	10.8	11.2	13.1	12.9	12.6	-	9.9	8.7	10.6	11.3	9.9	9.3
Root-mean-square error, $\left(\overline{\sigma_{s'}^2}\right)^{1/2}$	3.4	6.2	6.4	5.9	6.8	-	2.4	3.9	4.6	4.5	4.5	4.9
	Fall						Winter					
6 to 11	345	169	268	349	192	52	323	154	178	281	126	12
11 to 16	62	46	105	126	58	15	117	73	152	194	75	5
16 to 21	22	2	29	20	24	4	45	22	60	58	37	3
21 to 26	5	1	8	15	7		12	2	26	24	25	1
26 to 31	3		6	9	6		5	1	9	16	11	
31 to 36	1		2	3	1		6	1	6	10	2	
36 to 41				1	1		3	1	3	8	2	
41 to 46				1			1	2	1	6	2	
46 to 51				1					1	1		
51 to 56				1				1		2		
56 to 61											2	
61 to 66								2			1	
Total	438	218	418	526	289	71	512	259	436	600	283	21
Total soundings	181	181	173	156	113	23	177	173	159	135	74	3
Average number of shear layers per sounding	2.4	1.2	2.4	3.4	2.6	3.1	2.9	1.5	2.7	4.4	3.8	7.0
Root-mean-square shear, $\left(\overline{s'^2}\right)^{1/2}$	10.2	9.5	11.7	12.0	11.6	9.7	11.9	13.9	15.0	15.2	16.1	-
Root-mean-square error, $\left(\overline{\sigma_{s'}^2}\right)^{1/2}$	2.9	4.7	5.4	5.1	6.7	5.3	3.7	6.8	7.5	6.9	8.4	-

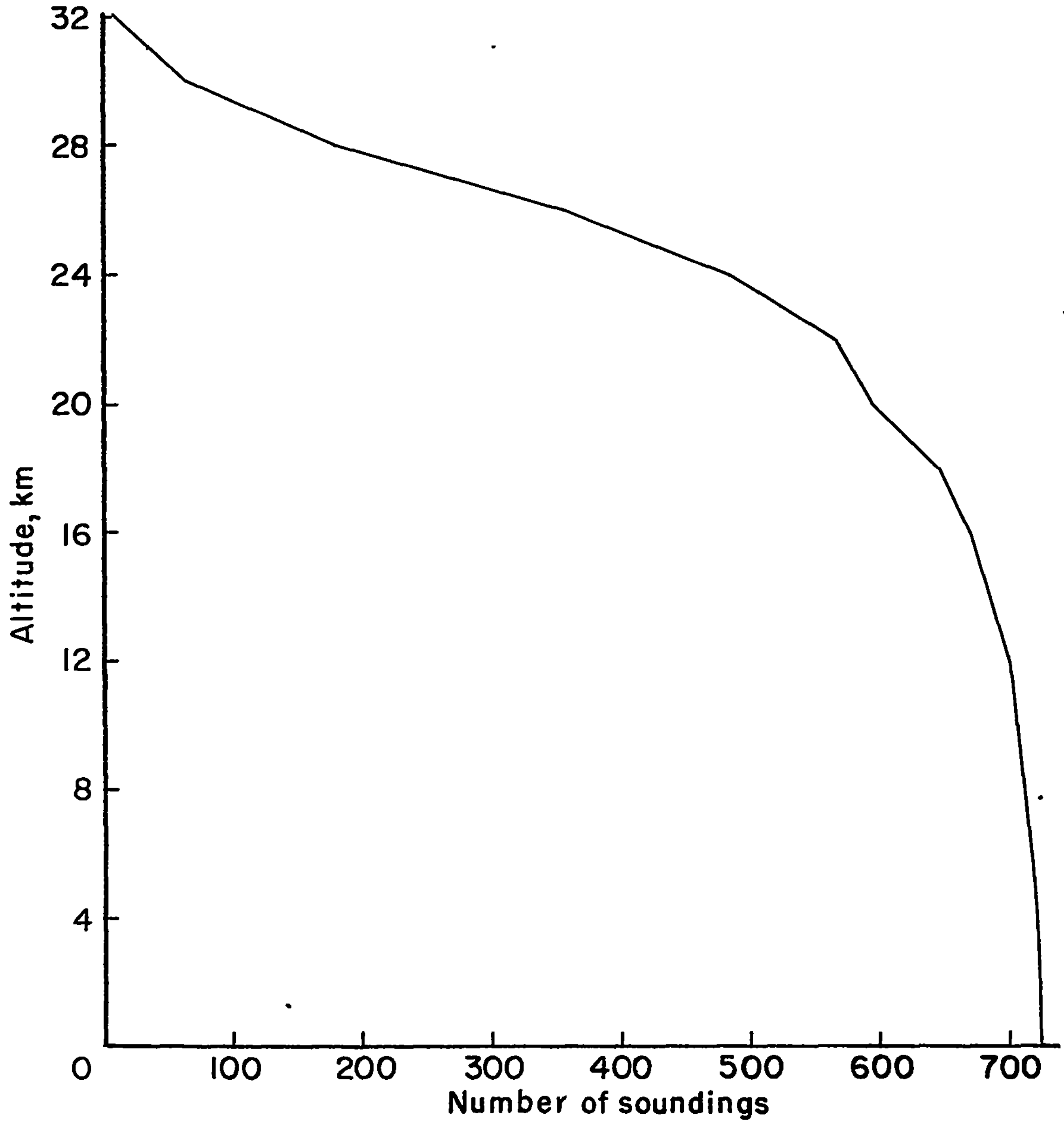
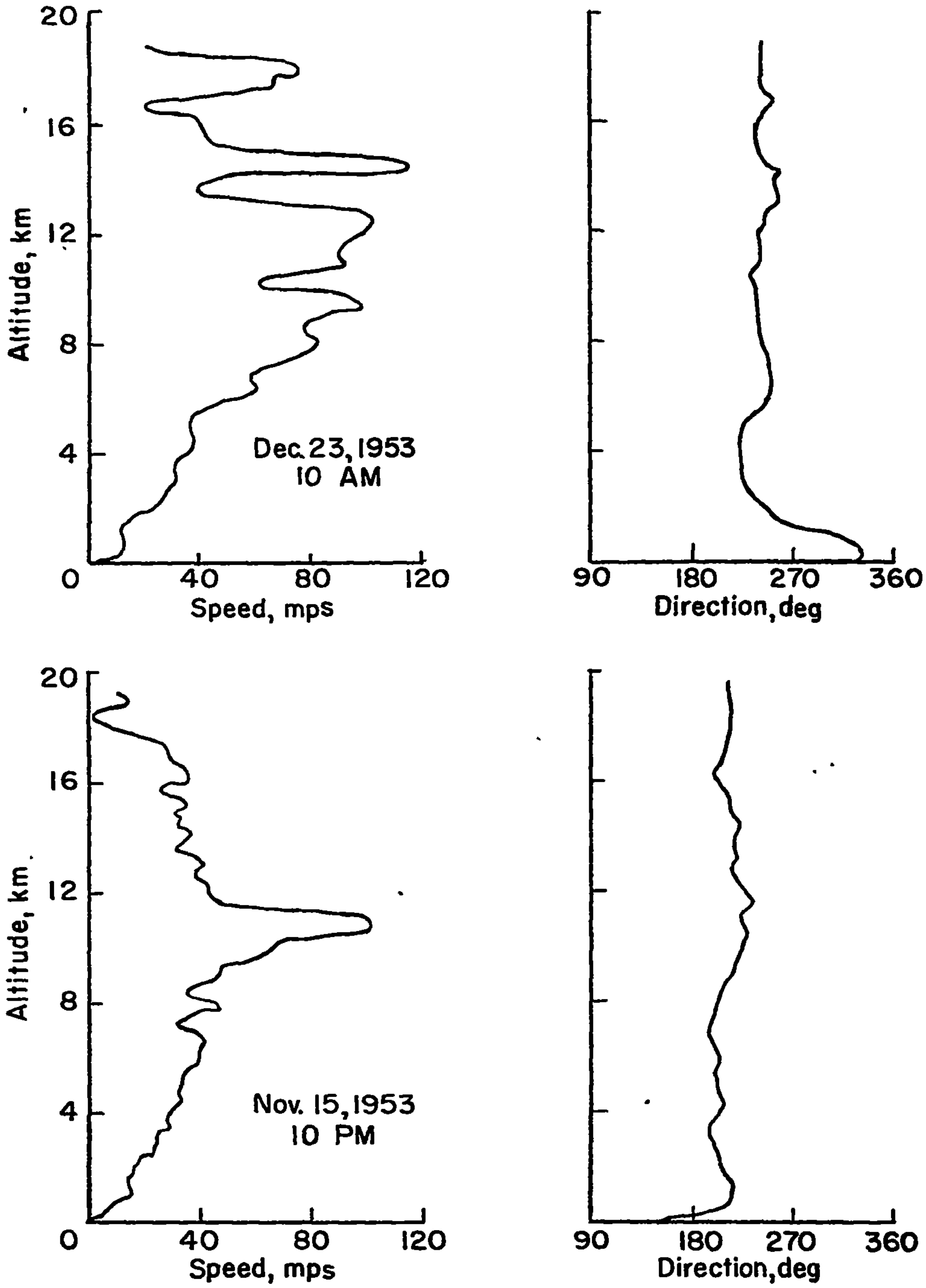
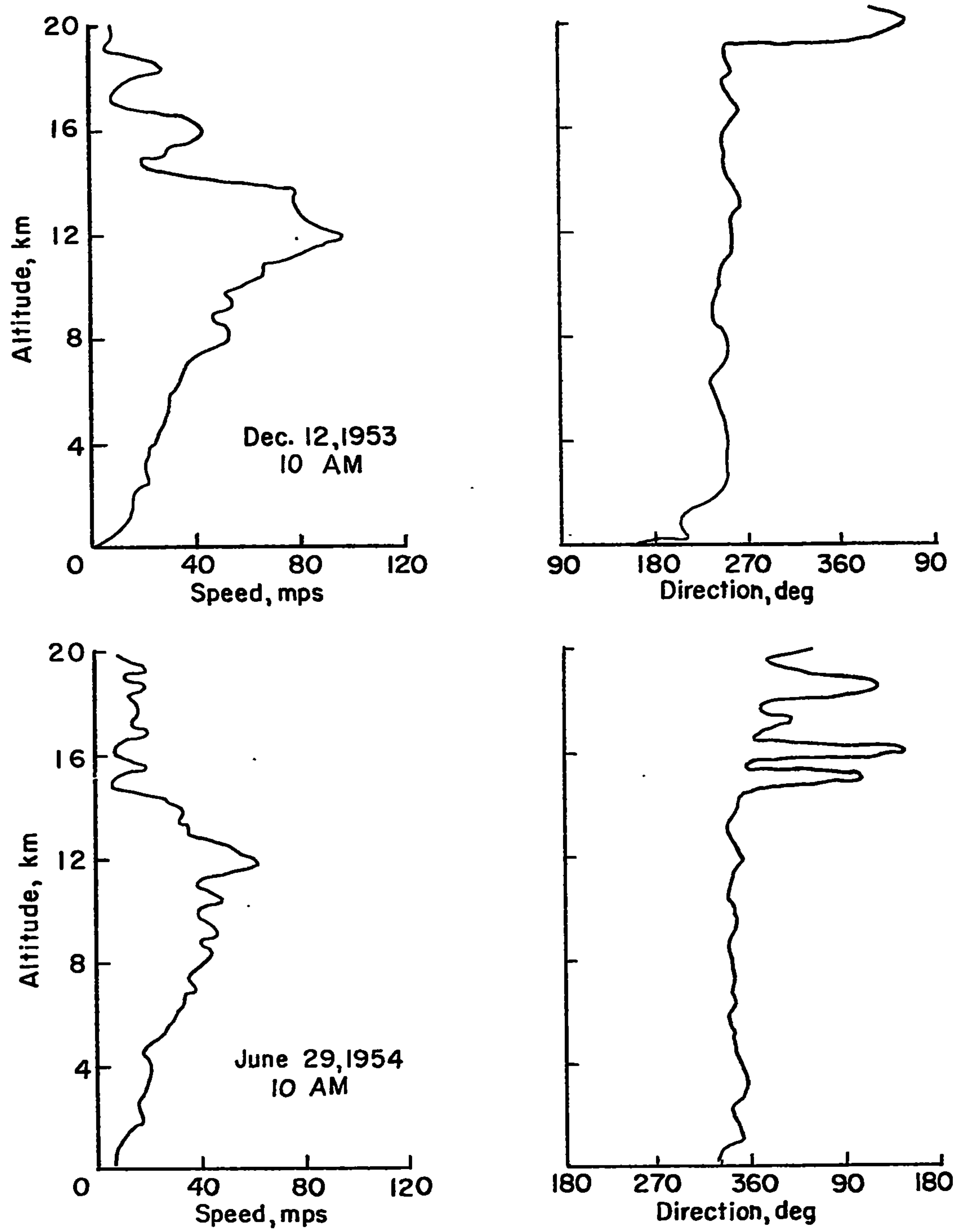


Figure 1.- Number of soundings reaching various altitudes for one-year observations used in present study.



(a) Large variations in wind speed.

Figure 2.- Samples of wind data.



(b) Large variations in wind direction.

Figure 2.- Concluded.

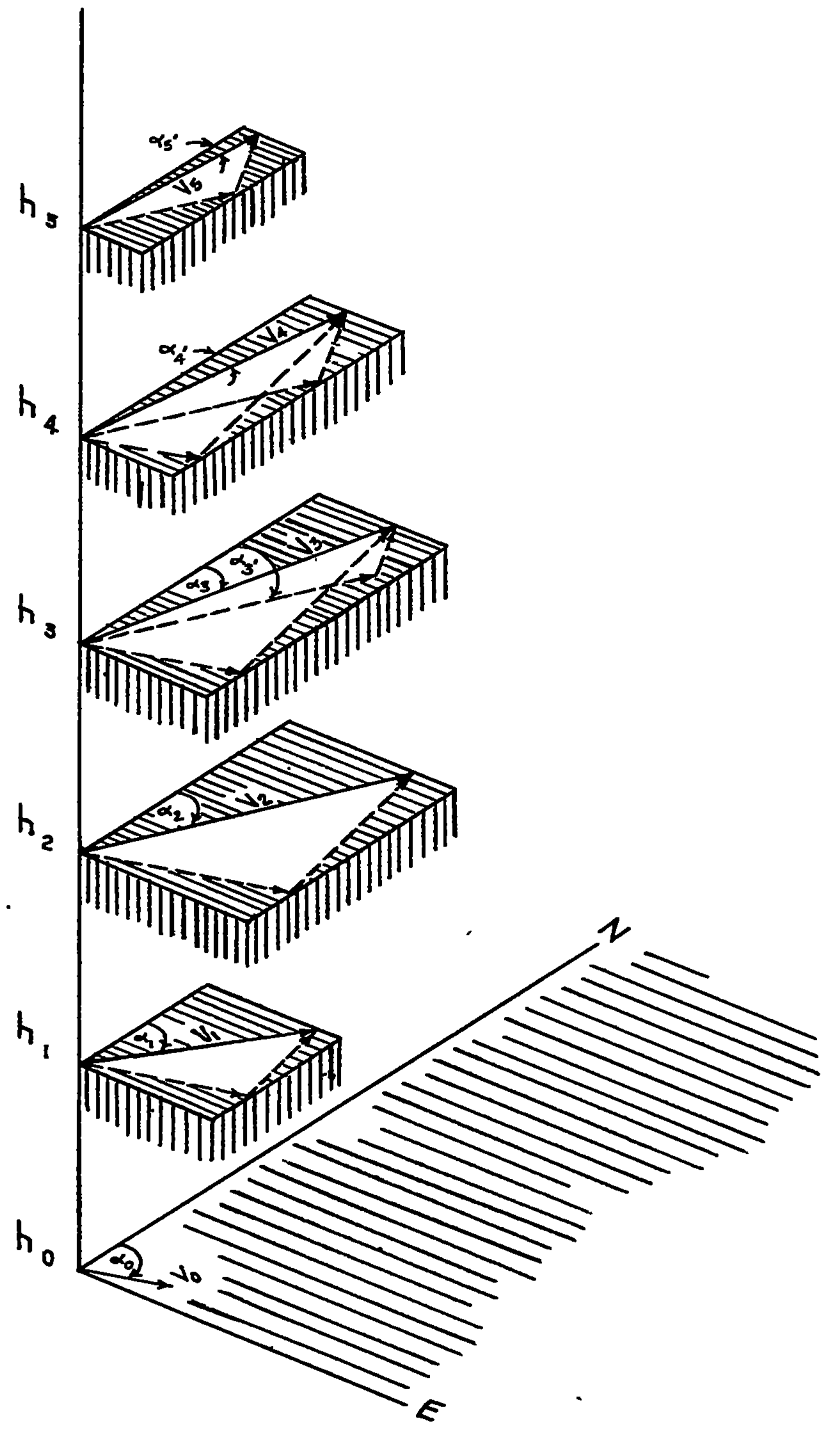
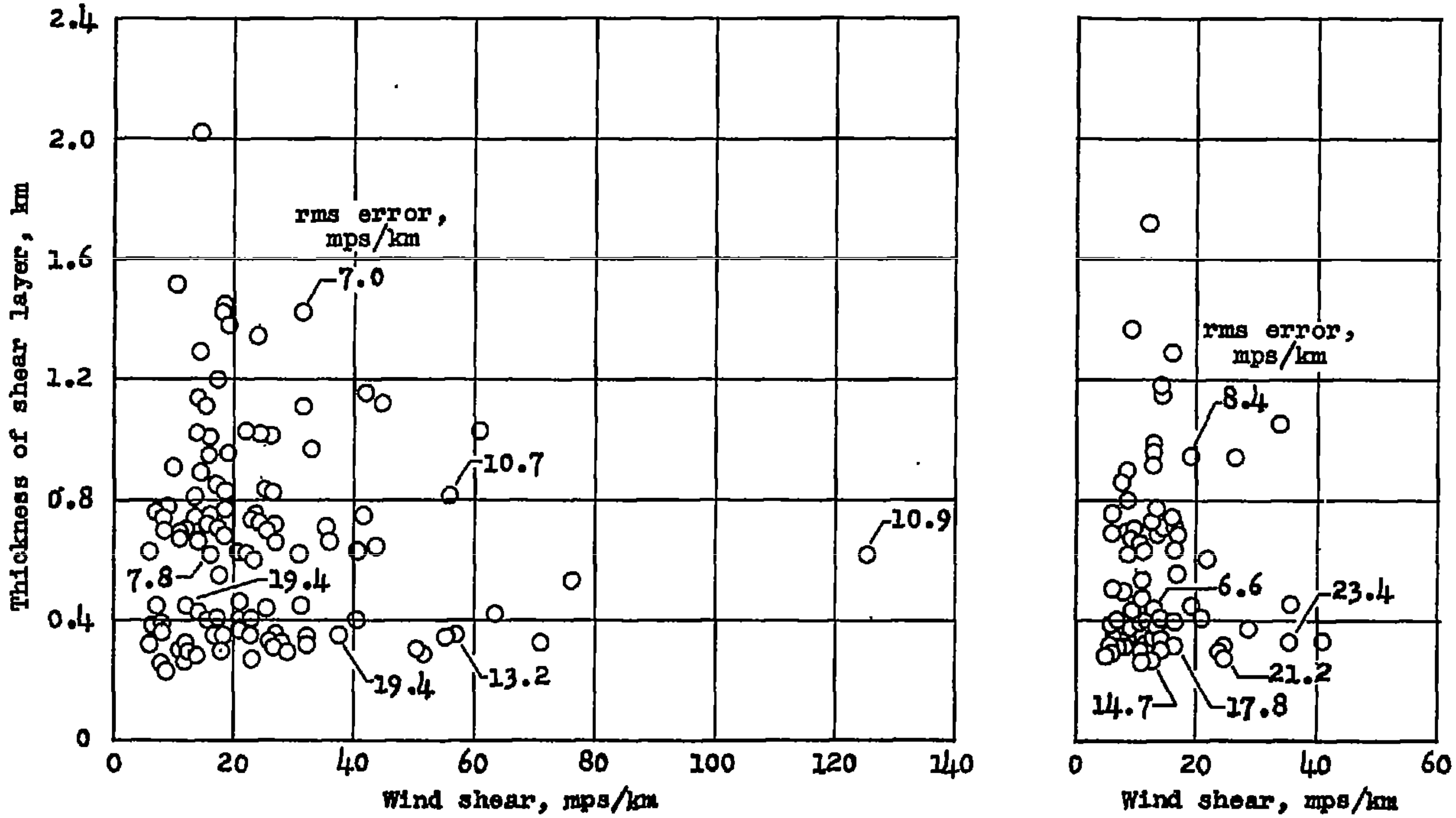


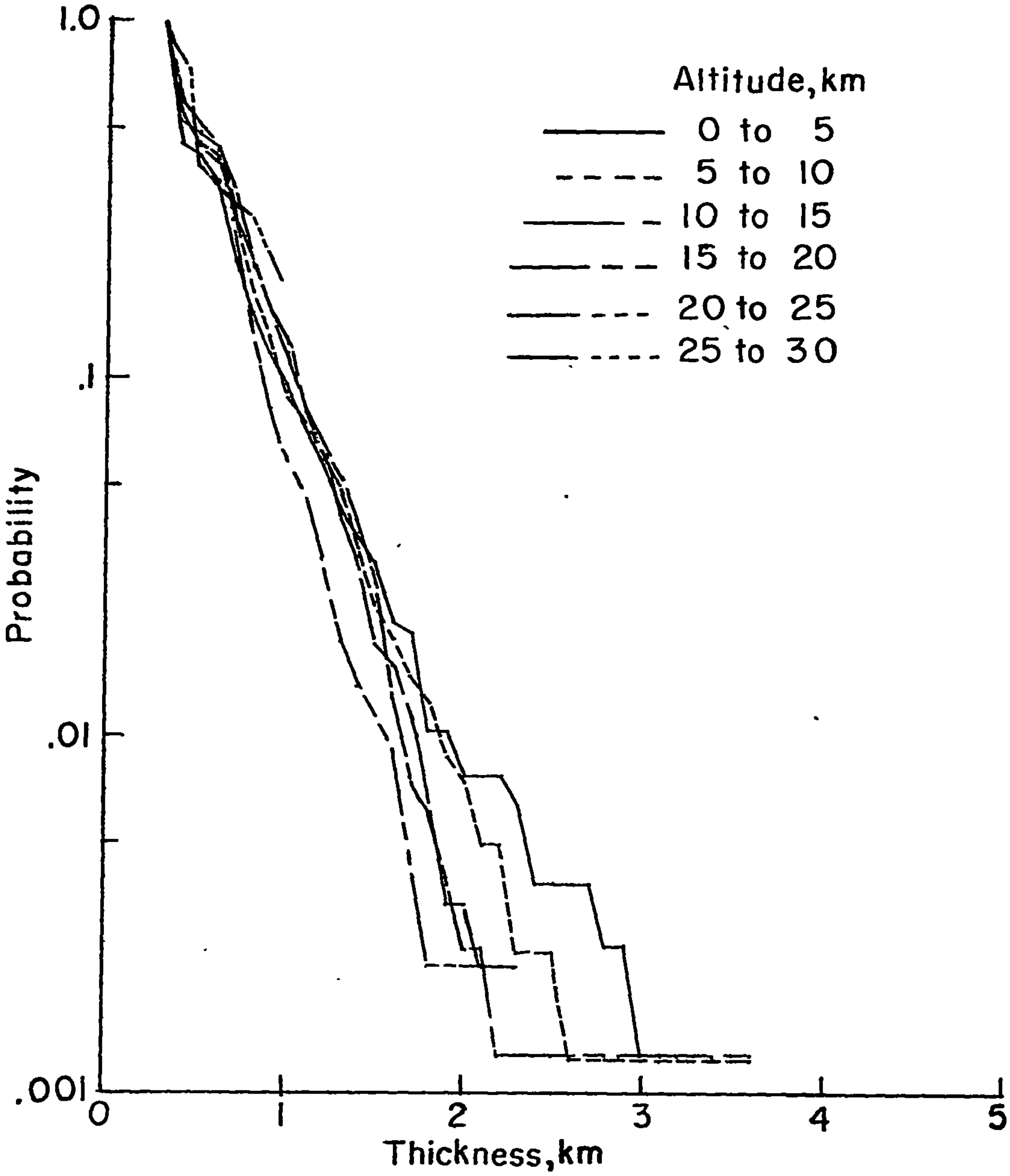
Figure 3.- Illustration of method for evaluating wind shear layers from soundings obtained from AN/GMD-1 rawin system.



(a) Longitudinal component.

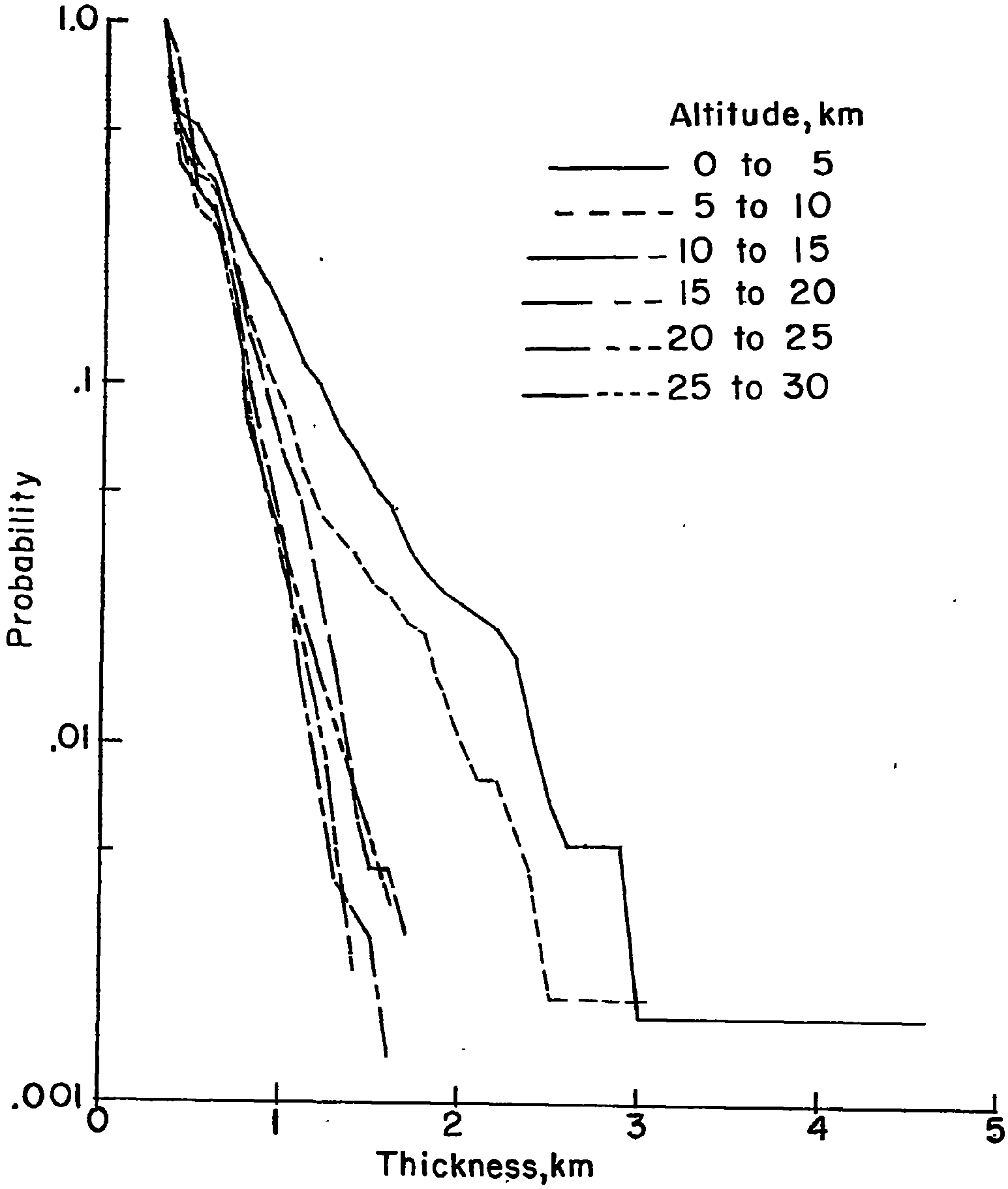
(b) Normal component.

Figure 4.- Variation of wind shear intensity with thickness of shear layer for longitudinal and normal shear components (10- to 15-kilometer altitude interval).



(a) Longitudinal shear components.

Figure 5.- Distributions of thicknesses of shear layers for different altitudes during the winter season.



(b) Normal shear components.

Figure 5.- Concluded.

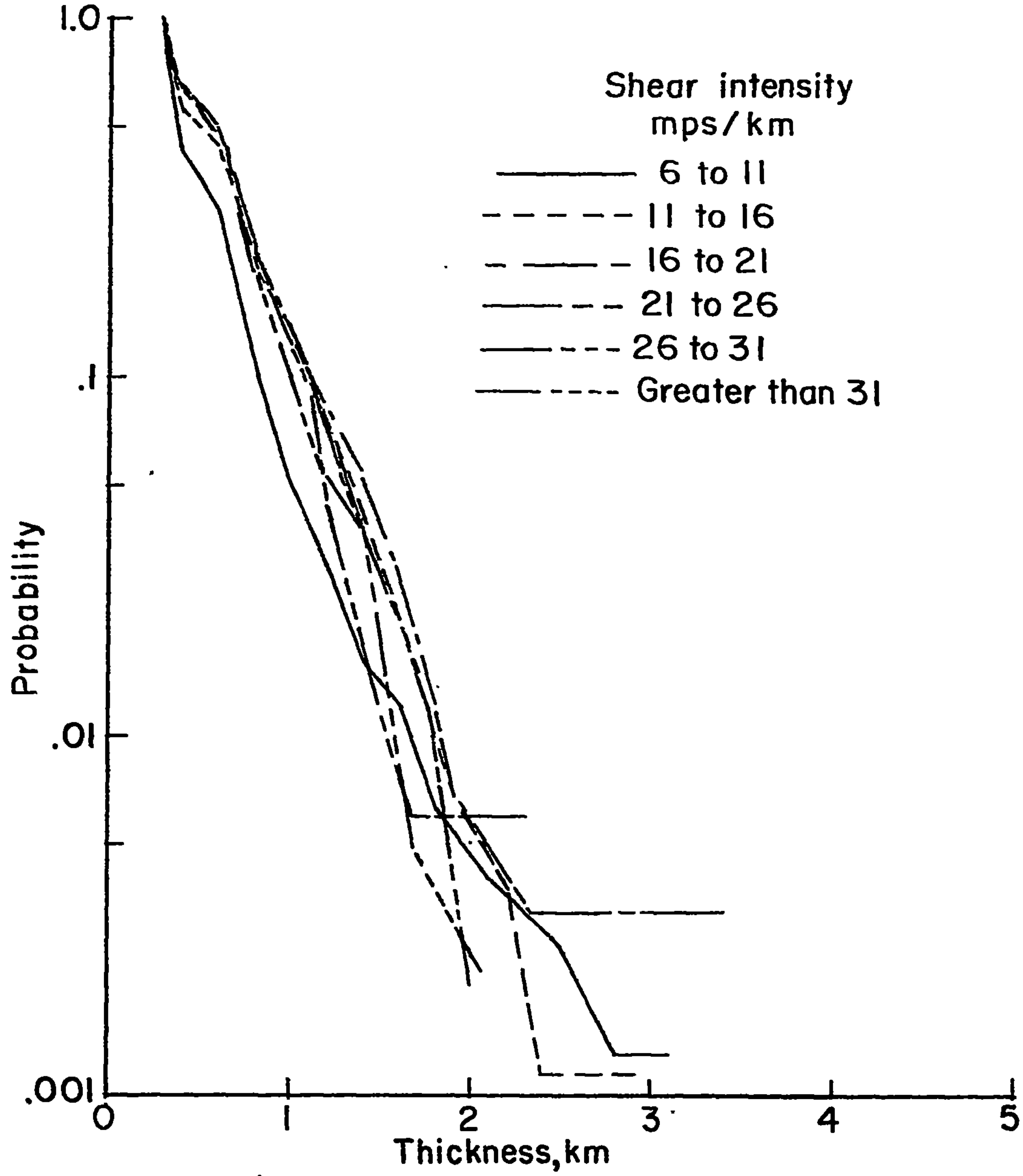


Figure 6.- Distributions of thicknesses of layers of longitudinal shear for different shear intensities during the winter season.

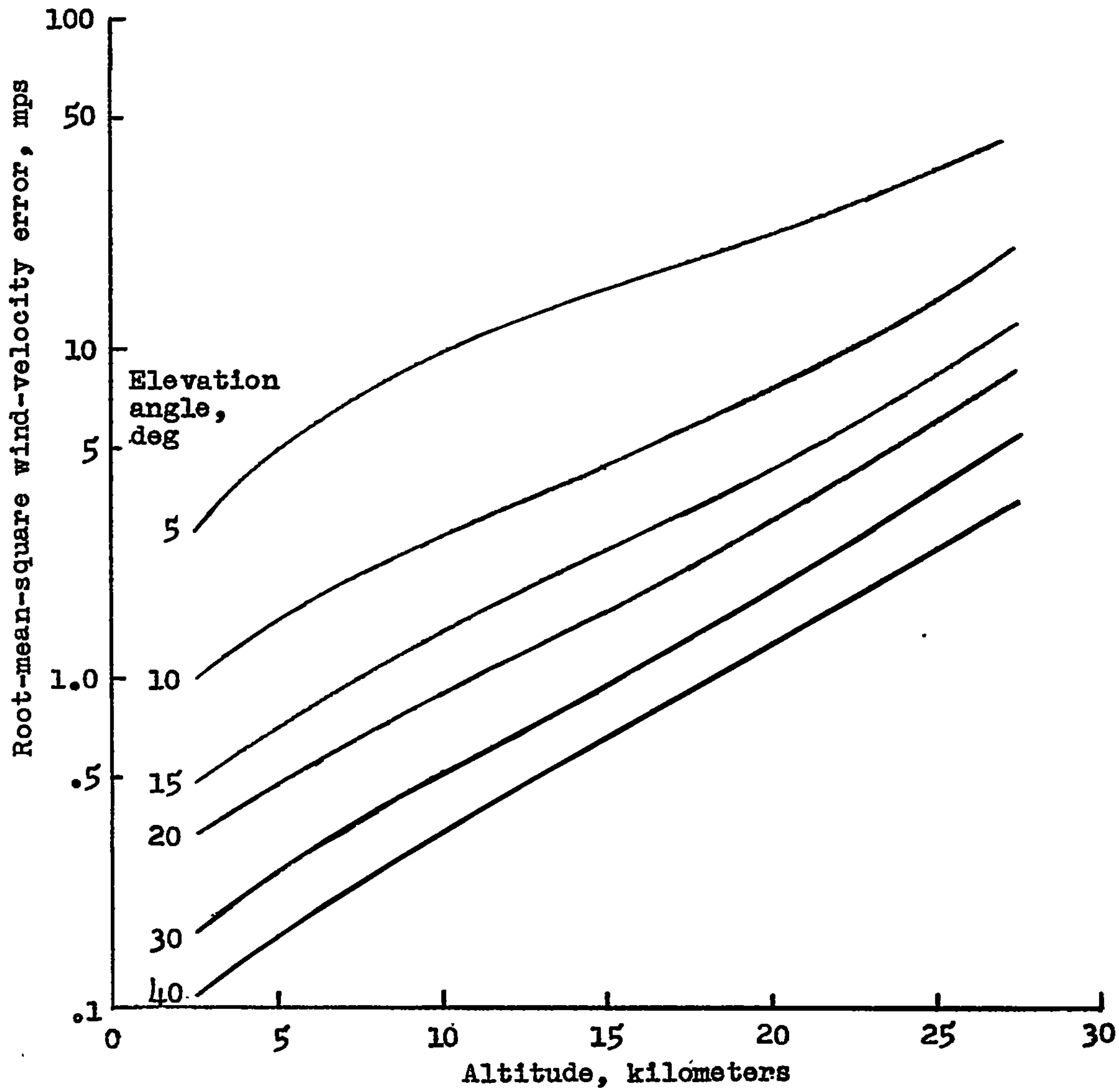


Figure 7.- Root-mean-square wind-velocity error resulting from inherent errors in AN/GMD-1 rawin system.